Hurricane Weather and Research Forecast (WRF) Model Workshop
Arlington, Virginia, 29-30 May 2002

Introduction:

This workshop was convened to address the near and far term theoretical, observing and modeling challenges in anticipation of developing the next generation operation hurricane prediction system to become operational at the National Weather Service/National Centers for Environmental Prediction (NWS/NCEP) during 2006. A broad cross-section of researchers, research and NWP modelers, operational forecasters, and those managing governmental and university research programs gathered at the National Science Foundation Headquarters in May 2002 to begin to identify the scientific challenges and to discuss potential avenues for dealing with those challenges.

The context for this workshop, in both the NWS and USWRP frameworks, was provided by Steve Lord [NCEP/EMC and Naomi Surgi [NCEP/EMC, and the USWRP Program Office]. Russ Elsberry [USWRP Lead Scientist for Hurricanes at Landfall] provided a summary of the San Diego workshop held in conjunction with the AMS Tropical Meteorology meeting in April 2002 in which scientists from the global tropical community provided input on the scientific aspects of the tropical cyclone forecast and modeling problem.

To set the scene for the challenges that lie ahead, the workshop began with Richard Pasch [NHC/TPC] and David Reynolds [NCEP/HPC] presenting updates on current numerical forecast model capabilities. A vision of the ongoing numerical model development was provided by a range of researchers from NCEP/EMC, NASA and the University community. This was followed by two working group sessions: I. Observations to address the hurricane initialization problem that was geared toward the upgrading the Gulfstream IV aircraft and II. Modeling physical processes for a high resolution coupled Air/Sea/Land hurricane prediction system. The working groups were tasked with identifying mature research for transition to operations in the near-term and potentially important research that could, with a focused effort, transition to operations before the end of the current decade. A summary of the workshop presentations and findings is given in the following report: the key recommendations of the two working groups are presented first; these are followed by summaries of the individual presentations; finally, the appendices include the workshop agenda, lists of workshop participants and working group members and the full reports of the individual working groups.

We thank all of the contributors to this report, including all of the speakers and workshop attendees. Thanks to Steve Nelson and colleagues at NSF for providing the support for the workshop.

Jenni Evans and Naomi Surgi
Workshop Conveners
January 2003

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Workshop Report and Overview

Executive Summary

The Weather and Research and Forecast (WRF) system is currently under development by the U.S. weather research and operational modeling communities. The WRF will replace current mesoscale modeling capabilities for various mesoscale forecast applications at operational NWP centers including NCEP and AFWA beginning in 2004. The WRF for hurricane forecasts (HWRF) will replace the GFDL hurricane prediction system at NWS/NCEP in 2006. The HWRF will serve as the nations next generation operational hurricane prediction system, as well as serve as the primary research hurricane model to replace the MM5.

Although significant progress has been made over the past several decades in advancing our Nation's hurricane track forecasting capability, many forecast challenges remain that need to be addressed by the next generation hurricane prediction system: advance forecast skill for difficult track scenarios that include erratically moving storms, storms that accelerate, storms that stall; improve intensity forecasts and provide a better description of the complexity of the hurricane surface wind field; and improve precipitation forecasts for landfalling storms associated with the inland flooding problem which now accounts for most of the Nations hurricane related fatalities.

To meet the above forecast challenges, significant advances must concurrently occur in advanced observations, data assimilation techniques and model development for both the hurricane environment and the hurricane core to properly simulate the complex interactions between the physical and dynamical processes on different scales of motion that describe hurricane motion and to capture intensity changes over the open ocean and hurricane landfall.

The HWRF will be a high resolution coupled air/se/land hurricane prediction model with advanced high resolution physics. Other advancements in the HWRF system will include a local advanced data assimilation capability to address the next generation initialization of the hurricane core circulation.

The U.S. Weather Research Program (USWRP) was designed to bring together researchers and the operational community to meet such challenges as these. It is under the auspices of the USWRP that this workshop was convened to begin discussing (1) the structure of the next generation hurricane forecast model, (2) the data and data assimilation techniques needed both to initialize this model and to provide direct forecast support and (3) the key impediments that must be addressed by the research community to support the operational implementation of the HWRF in the 2005–2007 time frame.. Specific attention should be directed towards the development of a suite parameterizations that are tailored to the hurricane forecast problem for both the hurricane environment and on the hurricane scale. The special data needs for observing such an intense mesoscale phenomenon in an otherwise weakly forced environment must also be addressed. These were the goals presented to the broad cross-section of researchers, modelers, operational forecasters, physicists, data assimilation scientists, and those managing governmental and university research programs who gathered at the National Science Foundation Headquarters in May 2002.

Two break-out groups were formed. One dealt with observations and data assimilation for the hurricane core to address the hurricane initialization problem using advanced variational data assimilation techniques. Special attention focused on upgrade plans for the NOAA G-IV to provide radar data to describe the three dimensional structure of the vortex from high altitude to the surface which may be supplemented with the NOAA P-3 data where available. This effort is critical to advance the intensity forecast problem.

Break-out Group I Key Recommendations on Data Needs for the WRF

This working group was asked to define the data types, sources, and strategies needed to initialize the hurricane WRF model. Their focus was on observations targeted to best initialize the vortex in the model using the hurricane WRF data assimilation system [DAS] (yet to be defined).

a)**Necessary types and resolution of observations to define the hurricane core circulation (in priority order)**

1) **Three-dimensional wind structure** with radial resolution of 0.5-1.0 km, height resolution 100 m in the ABL, outflow, and to resolve eyewall slope and at least wave number 2 azimuthal resolution (Highest priority)

2) **Moisture**, especially its vertical structure, is essential for validation and especially critical in environment surrounding core. Critical need for 100m height resolution in the ABL, with at least wave number 1 azimuthal resolution and 10-20 km radial resolution

3) **Temperature** profile structure is also essential for validation. The mean vertical profile [with 100m in ABL and near the tropopause] plus 10-20km resolution in radius and wave#1 in azimuth would be extremely useful for validation

4) **Ocean temperature and heat content structure** between center and 200-250 km (24 h) ahead of storm are essential for verification. Need 10-20 m vertical resolution in the oceanic mixed layer and resolved structure both radially and azimuthally from the storm center.

5) **Microphysics/rain/reflectivity distributions** are all essential for verification: their vertical structure is critical so resolution of 250m is needed to resolve the melting level. Need 1km radial resolution to resolve the eyewall. Azimuthal resolution least critical, but desire at least wave number 2.

6) **Ocean waves** are essential for verification: at least wave number 2 azimuthal structure is critical for resolving asymmetry in wave height and length. Radial structure of 20-50 km is needed in order to be capable of resolving the radius of 8’ and 12’ seas.

7) **Ocean currents** are essential for verification.

8) **Radiation** is essential for verification.

b) **Instrumentation upgrades needed for aircraft (in priority order)**

Note: A much larger candidate instrumentation list was considered by this group – see Appendix D for the complete list of instruments, the observations each was targeting and its perceived limitations. Also the current instrumentation upgrade for the G-IV is under review and may be revised as needed.

1) **Communications to the ground to transfer the data to the model DAS** – need a secure high-speed (at least 9600 bd) data communications link to the ground. Systems on the WP-3D currently are 100 bd ASDL, 2400 bd INMARSAT, and 9600 bd Globalstar. G-IV has 2/2400 bd INMARSAT systems and looking at 64000 bd upgrade.

2) **Doppler wind capability**: WP-3D has the ideal system, but doesn't fly high enough for the moisture and temperature requirements. G-IV has a nose radar that has Doppler capability, but not in the vertical. Looking at test of vertically pointing scanning Doppler radar (airborne profiler) for G-IV. (This is the top priority and is essential to EMC's vortex initialization effort)

3) **Surface wind and rain**: HRD and UMASS have developed SFMR to provide surface wind and rain estimates. Working with AOC on version that could be used on all AOC aircraft
The following are less of a priority for EMC:

4) **Moisture profiling**: NASA (through CAMEX) has developed DIAL Laser (LASE) system for use on DC-8. Provides continuous vertical moisture and aerosol profiles above and below aircraft along flight track when not in heavy cloud. Not sure whether suitable for AOC aircraft.

5) **Temperature profiles**: NASA (through CAMEX) has developed microwave temperature profiler (MTP) system for use on DC-8 and ER-2. Provides continuous vertical temperature profiles 4-5 km above and below aircraft along flight track. Should be suitable for AOC aircraft.

Break-out group II Key Recommendations on high resolution coupled modeling of hurricanes

Evaluation of the desired components for a fully coupled land/sea/air hurricane model was the charge of this working group. Recommendations were prepared in the context of (1) **Short-term research**, ready to transition in 2005 time frame. Research identified in this category is candidate for inclusion in the Hurricane WRF Version 1 [HWRF-V1]; (2) **Longer-term strategic research** unlikely to be mature by 2005, but having good potential to contribute to later versions of the HWRF, contributing to ongoing HWRF development by 2008. In addition, workshop participants were asked to identify HWRF goals that take advantage of common objectives in other programs [such as CAMEX and CBLAST]. Key scientific questions identified in the working group are outlined here, followed by [un-prioritized] recommendations for HWRF characteristics, testing, validation, and supporting research in the next 3–6 year time frame.

a) Fundamental questions on hurricanes where HWRF-related research is needed

1) **Parameterization at smaller scales**, for example below 4 km, may not work for some processes. Studies are needed to determine what scales can be resolved. Further, it is likely that convection has to be implicit in the model and not parameterized as is generally the case.

2) **Grid sizes of ≤1 km should be able to resolve the largest eddies** in the hurricane boundary layer. Even in models with a 1 km grid, those eddies are still parameterized, yet the fact that they are also beginning to be resolved leads to concern about "double counting" [artificially enhancing] the effects of turbulent processes in some flow regimes and over-smoothing turbulent flows by excessive mixing in others. Fundamentally, how does one paramaterize turbulence when the grid size approaches the size of the turbulence and a wide range of spatial and temporal scales is important for flow development?

3) **Important features of shallow layer convection** will still be difficult to resolve on a grid size of 1 km.

4) **The transition from the physics of the inner bands** to those of the outer core are not known at scales even at 4 km. While the mesoscale processes in the eye wall are important to understand, how critical are they to improving the forecast of track and intensity in the coming five years?

5) **Rainfall estimations** over water are critical to understand the energy balances. Those estimates are poor at best.

6) **The entire understanding of the phase changes of moisture** needs serious review. For example ice formation in updrafts is poorly understood and the role of graupel needs much better definition. Parameterizations of the phase changes range greatly in sophistication and none seem to give reliable results when compared to available observations.

7) **Changing grid sizes, as when using nested grids**, can mask important physical processes, including turbulence. Serious issues exist on how to use different boundary layer physics in a model with several nested grids. How does one make the transition from a physical process being implicit in the model on one nest and parameterized in the same model on a different nest?

8) **The HWRF should be useable across all of the grid sizes**. However, because so many questions remain unanswered at the smaller scales, realization of that capability is well into the future – past 2005. Much testing and evaluation at different resolutions need to be carried out.

9) **Virtually all available research cases and statistics exist for the most intense 50% of storms**. This not only biases the statistics, but ignores the very different importance of physical processes that occur in the weaker as opposed to the stronger storms. The weaker storms making landfall often cause the largest damage from flooding.

b) Short-term research to transition to HWRF by 2006

1) **A fully coupled modeling system**: The HWRF model is intended to be a state-of-the-science coupled atmosphere, ocean, wave and land surface model. In the initial implementation, the working group recommends a goal of 4 km horizontal resolution, consistent across all of the coupled model components.

2) **Nesting**: to reach resolution goals for the hurricane core, development and evaluation of a coupled, moveable, nesting capability is recommended.

3): **Component model selection**: wave and ocean model selection and WRF configuration testing must be completed.

5) **Ocean and interface models:** wind/wave coupling strategy should be developed; Vertical mixing parameterizations for ocean models should be evaluated against observed data. Work should progress towards ocean model assimilation system.

6) **Validation**: standardized atmosphere and ocean evaluation and validation packages – including a suite of test storm cases – should be developed to assess the impact of future model upgrades. The variables included in this validation suite should include fields useful for direct model evaluation and elements needed directly to contribute to NHC forecasts.

7) **A web page-based configuration inter-comparison** framework must be implemented: any researchers contributing to this site will be required to report a set of standardized metrics, including runtime as well as physical forecast evaluation measures such as storm track, intensity and structure evolution.

8) **A general infrastructure for end-to-end model testing and transition** [e.g. data assimilation, model forecast, post-processing] must be developed. This should include model testing requirements and acquire computer resources necessary for research development and testing for future operational model upgrades. All potential transition activities should be closely coordinated with NCEP to ensure all data formatting standards and coding standards be met.

9) **New results on sea spray/surface flux effects** on the PBL should be closely diagnosed and tested for potential transition to the operational HWRF.

c) Longer-term strategic research: impact on HWRF development by 2008

1) **Appropriate treatment of sub-grid turbulence** at grids on resolution of <5 km needs immediate attention, particularly for grid spacings of 1–2 km or less. This should include interaction between the turbulence Parameterization and the grid-resolved mixing [the issue of "double counting"] as well as turbulence and micro physical parameterization interactions on these scales. Preliminary research indicates a solution bifurcation at these higher resolutions.

2) **The effect of wind/wave coupling on momentum flux** needs further exploration.

3) **Wave/current coupling** and effects on mixed layer have yet to be addressed in the hurricane modeling context.

4) **Air/sea (sea spray) exchange** affects the boundary layer structure and microphysics, especially in the core and rain bands. The effects of these exchanges have been little more than hinted at by current research, but warrant further study to quantify their importance.

5) **Sensitivities to shallow cumulus convection need** attention.

6) **Microphysics**: initialization, ice distributions and habit are all of concern as the model grids shrink and the problem of parameterizing convection essentially shifts from the theoretical cloud model and its closure to the explicitly resolved cloud-scale motions and parameterized effects of their microphysics .

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Final Report

1.0 Welcome, Introduction and Purpose of the Workshop (Stephen Lord/Naomi Surgi, NWS Environmental Modeling Center)

Steve Lord and Naomi Surgi welcomed the participants to the meeting, which was the first general, scientific meeting on the HWRF modeling system. The WRF program overall is to provide the community with a full-range of Numerical Weather Prediction (NWP) model capabilities that include such things as model software architecture and physics, data assimilation, input/output applications interfaces, testing and verification, documentation, standards, as well as a framework within which to develop and test new theories, models and capabilities. The WRF is a community effort that provides a modeling infrastructure to run on a number of platforms such as IBM at the National Centers for Atmospheric Research (NCAR) , Alpha-Linux system at Forecast Systems Laboratory (FSL) , and Linux PC systems. The WRF community based models will be open to both university and governmental organizations.

Within the overall WRF activities, the hurricane modeling system is seen as a particular sub-set with unique characteristics and issues. The HWRF will be a coupled land/sea/atmosphere model. The HWRF will have a nested wave model coupled to the ocean model and the land surface model will be coupled to hydrology to address the inland flooding problem. Development of this advanced hurricane modeling system will provide a unique opportunity for collaboration between the research and operational communities to combine a variety of expertise that is necessary for the successful modeling system development.

Lord and Surgi challenged the workshop participants to consider the data needs for such a hurricane prediction system – including assimilation issues, as well as considering the configuration of the optimal coupled land/sea/atmosphere model for the hurricane forecast problem and any roadblocks to achieving either the data or modeling goals. They charged the workshop participants with beginning to design, through working group sessions, a pathway to implementation of the next generation hurricane forecast model.

2.0 Summary of San Diego Workshop (Russell Elsberry, Naval Postgraduate School)

The workshop, the second of two sponsored by the USWRP, was held 3-4 May 2002, in San Diego after the 25th Conference on Hurricanes and Tropical Meteorology. The main objective was to discuss the issues involved with the design of a "best possible" hurricane research model containing a high level of detail. A significant part of the meeting was given to exploring what was known, and what still needed to be addressed. Specific aims of the San Diego workshop were to:

1. Explore what is understood of tropical cyclone intensity and precipitation as a basis for numerical modeling.

2. Identify the minimum characteristics required for a research and an operational prediction model.

3. Formulate recommendations on the research required to support:

a. The specification of surface flux coefficients in high wind situations, and
b. The specification of water droplet species, their sources and conversions.

4. Identify the science pathways needed to obtain knowledge through observations and field programs.

5. Establish ways for modelers and researchers to collaborate on model testing, sharing code, etc.

6. Discuss ways for people in a number of countries to share research results and operational experiences on tropical cyclones.

It was noted that the first hurricane models exhibiting some skill in providing intensity forecasts are just becoming available. While the ultimate objective is to provide an operational capability, substantial research is required before that objective can be addressed properly. One of the critical questions addressed was "What needs to be done to improve the forecasts of storm intensity and precipitation over land?" The workshop established goals for research into both storm intensity and precipitation forecasts. Heavy rain events are one of the particularly difficult issues to be addressed, in part due to the lack of verification. Desirable characteristics of a research hurricane model were also defined at the workshop.

Frictional effects and ocean surface wave processes were identified as areas where understanding and information were particularly lacking. It is especially important to know how to handle such subjects as sea spray, ice microphysics, triggering of the outer convective bands, and horizontal mixing. Workshop participants noted that observations that would define the initial features of the eye wall and the rain bands are presently lacking; information on the microphysics and moisture were missing and difficult to obtain; data assimilation and communications bandwidth for satellite information need urgent attention.

One of the points raised during the discussion was that track forecasts had received the emphasis in the past, but that emphasis seemed to be shifting to intensity and precipitation forecasts. With respect to the precipitation, the first issue is to deal with the correct track and intensity forecasts. Once that has been achieved, then it is important to relate the precipitation to the watersheds for input to the hydrologic models. The report of the workshop can be found at: <http://box.mmm.ucar.edu/uswrp/>

3.0 Summary of Presentations

A. Forecaster Assessment: Present and future forecast challenges

A.1 Operational Hurricane Forecasting at the NWS (Richard Pasch, TPC/NHC)

Richard Pasch gave an overview of the procedures used at the Tropical Prediction Center (TPC) for issuing the forecasts. The time between when the model output is available and the forecast has to be issued is very short. The coordination session between the Department of Defense (DOD) and the National Weather Service (NWS) is held at T+2 hours, before the forecast is issued. The types of issues that have to be resolved during the coordination session are:

1. Predicting tracks of erratically moving storms.

2. Precise prediction of landfall.

3. Intensity prediction.

4. Extreme rainfall events.

5. Surface wind distribution, in particular the size and shape of the area of wind speeds of 34 knots and greater resolution of the differences in the model forecasts. The dropsonde information can make a significant difference in the quality of the model forecasts.

Some of the outstanding forecast issues identified by the forecasters at the TPC include:

1. A serious problem persists with over-warning in both track and intensity, but there has been improvement in recent seasons. The most significant improvement has been in the 2–3 day forecasts of track; these advances are due to improvements in the models.

2. Intensity guidance is an area still needing improvement, particularly for intensifying storms.

3. Rainfall characteristics vary substantially over space, and are not well forecast. These variations have significant impact on the forecasts for flooding as it is not always possible to define the watershed that will be most affected.

4. Forecasts of wind radii (areas of strongest winds) are not good: the guidance tends to over predict the strongest winds. Forecasters are looking for assistance from improvements in the dynamical models for both precipitation and surface wind intensity forecasts.

5. There is a strong tendency to over specify the region for landfall. That is, too much of the shoreline is included in the landfall forecasts. There has not been significant improvement in 25 years.

6. No single model seems to have the advantage over another for more than one or two years. The NCEP model has shown recent improvement for cyclogenesis. Overall, however, the genesis of a storm is not well predicted. As a summary statement, **the models have made important improvements in track forecasts, but not in the warning areas for landfall.**

7. There is a strong need to address the weak storm situations and other “outliers”: i.e. those storms with intensities that are infrequent.

8. Techniques for evaluation of forecast reliability.

Pasch concluded by iterating that the numerical prediction models have had substantial improvement in the guidance for track, lesser improvement for landfall, and that the forecasts of the critical features of quantitative precipitation and surface wind were not adequate. These latter forecasts were critical and posed some of the most serious challenges for the models.

A.2 Hurricane Quantitative Precipitation Forecasting (QPF) and Inland Flooding (David Reynolds, Hydrology Prediction Center)

The challenge here is to make a six hour forecast of the extreme events of precipitation. Then, predict the response of the rivers and streams in the affected watersheds. The more organized is the tropical storm, the more skill there is in forecasting rainfall amounts. As the storms move inland and the driving force changes from the oceanic-based circulation to land-based convection with convergence lines, the skill for precipitation forecasting drops rapidly. This loss of skill is shown in the threat scores. The forecasting skill is directly related to the ability of the models to handle this transition to land-based convective-driven rainfall.

At the moment, the AVN model handles tropical cyclone rainfall forecasts better than does the ETA. As a general statement, the models under predicted by a significant amount the heavy rainfall. Also, as a general statement, the models handle cool season rainfall better than warm season. The trend lines for the threat score for precipitation forecasting have not improved significantly during the past 30-40 years. What improvement there has been represents less than one day increase in skill. Specifically, the models have difficulty with the timing and location of the heavy rain, as well as with the magnitude. The temporal and spatial characteristics of the rainfall are not well predicted and spurious centers are frequent.

The deterministic forecasts of quantitative precipitation need to be replaced by probabilistic forecasts. This will require focused research. That research must also examine carefully the needs of the River Forecast Centers, and how they generate products for their users. Because there are few large rain events, and verification is spotty, the statistical base for these extreme events may not be reliable. That raises the question of whether or not areal quantities are sufficient for flooding forecasts, if the location and timing are good. Since more people have been killed by inland flooding than by the high winds and storm surge with a hurricane, the need for rapid improvements in quantitative precipitation forecasting is urgent.

B. Scientific Challenges for the Hurricane WRF

B.1 Air Sea Interaction (Dmitry Chalikov - NCEP)

The Hurricane WRF will be a coupled air/land/ocean model. The air/sea interaction processes are critical and need substantial additional research to understand and incorporate into the model. The most critical aspect is mixing in the upper ocean down to the thermocline. In fact, mixing at the thermocline surface can produce fast cooling of the upper layer.

Chalikov outlined some of the most critical research areas needing attention for the model development:

1. A high resolution, horizontal ocean model is needed based on a full set of equations for the thermocline physics and dynamics.

2. High vertical resolution is essential for the model in the lower atmosphere.

3. High quality parameterization of the vertical mixing in the atmosphere is required.

4. High performance Massively Parallel Processing (MPP) computer architecture needs to be developed.

5. Development of high resolution, nested ocean models running daily on MPP configured computers is required. These models need to incorporate local dynamics.

He went on to describe the Multi-Scale, Ocean Forecasting System in use at NCEP. This system is run daily, and uses a global ocean model forced by the global atmospheric model. The model is high resolution with a grid scale of ~8 kilometers with 37 vertical levels. The US coastal zone, regional model is forced by the regional atmospheric model and the boundary conditions from the global model. Any ocean model has to deal with very difficult processes such as the physical processes for the waves and spray, and the exchanges both within the ocean, and between the ocean and the atmosphere.

B.2 Surface Waves: The WAVEWATCH model (Henrik Tolman, NCEP)

Since 1994, NCEP has been running a third generation ocean wave model. The decision was made to build a new model, termed WAVEWATCH, based on the WAM, but with significant differences. WAVEWATCH became the operational ocean wave model in 2000.

WAVEWATCH is initialized by the global model and has versions customized for the Western North Atlantic and the Eastern North Pacific. All of the models use 24 directions and 25 frequencies for wave forecasts. There is a strong need to paramaterize due to the lack of both computing power and physics. For example, capillary waves are critically important, but are not included in the dynamic model and need to be parameterized.

Hourly wind fields are essential to capture wave field development, especially for rapidly moving, intense, small-scale hurricanes. Hourly wind field analyses were implemented in 2002 for the Atlantic hurricane season. Such hourly analyses are necessary to ensure continuity of the wave model and for swell forecasts. For example, there were no land falling hurricanes on the Atlantic coast in 2001, but there were deaths due to swell.

The ocean and atmosphere are coupled through various fluxes that are, themselves, a function of surface waves. Some examples of the coupling are:

1. Momentum is transferred from the atmosphere to the ocean by surface stress and subsequent wave actions.

2. The wave breaking and spray influence the fluxes of mass and heat.

3. Wave breaking also is a large source of turbulent energy in the upper ocean and the momentum in the waves is released during the breaking action.

One of the scientific issues that needs serious attention is that the momentum transfer and drag coefficients included in the models are extrapolated from moderate wind conditions. Information is not available at the low and high ends of the wind velocities. The errors introduced by this extrapolation have a first order impact on wave growth rates. In response to a question about resolution, Dmitry Chalikov said that two way nesting with moving nests needed to be made part of the wave model system to ensure coupling to the atmosphere.

B.3 Data Assimilation (John Derber, NCEP)

John Derber gave a summary view of the importance of data assimilation to NWP and some of the issues. The basic objective of the NWP data assimilation is to combine all relevant information from any source to produce an estimate of the most likely state of the atmosphere at the beginning of the forecast cycle. Generically, the "cost" or "fit" function, "J", optimizes the fit of the background field with the observations and other constraints. In some data sparse areas of the world, the background field is as good as the observations.

1. The first step is to convert the analysis (background field) to observation-like information and compare that information to observations. The forward models to make the conversions can be such things as a simple interpolation scheme, a complex radiative transfer function, or a precipitation algorithm.

2. The weights given to the various terms in the equations come from error covariances. Some of the difficulties encountered are that:
    a. Error covariances relative to "truth" are not known.
    b. There is considerable time and space variability within the error covariances.
    c. Background error covariances determine the horizontal, vertical and inter-variable distribution of information.

3. The final terms lumped under "other constraints", for example, force moisture to be non-negative, and keep a balance between mass and momentum in mid-latitudes. There are significant differences in the data assimilation issues for large-scale processes in the tropics and for hurricanes. The latter, for the most part, are mesoscale or smaller in nature. Clearly, data assimilation for hurricanes is much more difficult than for the larger scale tropical situation.

Some of the data assimilation challenges for the tropics and hurricanes include:

1. **Balance equations**: In the tropics (and for mesoscale in general), balance is dominated by moist processes and is much more complex than for the larger scales. Failure to properly treat the balance issues will result in a rapid loss of useful information at the beginning of the forecast. The increase in non-linearity due to moist processes make the tropical/hurricane problem more difficult to solve.

2. **Analysis variables:** In the tropics, to accurately analyze variables such as cloud liquid water and cloud ice, a balance has to be achieved and all the fields involved need to be initialized. That also means the surface and ocean fields must be correctly specified. The ability to achieve a realistic balance is not as straightforward as for the larger scales.

3. **Background error covariance:** For the tropics, it is essential to have situation-dependent error covariances, but they are difficult to determine. The structure of the background error covariances for cloud and surface fields, for example, are almost certainly to be dependent on small scale dynamics that are not well known. Further, it is critical to include in the background error covariances the relationships between the variables (e.g., water vapor and clouds).

The characteristics of observing systems, often either not well known or difficult to address, present a wide range of issues that have to be addressed in data assimilation.

1. Satellite/aircraft radiance data:
    a. Good horizontal resolution, but large areas are not covered due to clouds

    b. Poor vertical or along-the-beam resolution. This affects severely the ability to define the vertical extent of clouds and the boundary layer.
    c. The forward model (converting an analysis field to observation-like information) is complex and non-linear in the presence of clouds and/or precipitation. Surface emissivity over land, ice or snow often makes the observations unusable. Aerosols and constituent gasses affect the convergence adversely. The computing requirements are very high and the computational efficiency is low.

2. Doppler Radar
    a. The forward model is complex as one has to deal with the interpretation of reflectivity.
    b. Beam spreading makes the sampling problem difficult.

c. There are significant issues of quality control.

3. Ship Observations
   a. There normally is no information in the vertical.

   b. There is very little ability to extrapolate the surface observations upward into the atmosphere as very different atmospheric states can produce the same or similar surface data. In the free atmosphere, there are physical equations that can be used to extrapolate information from one level to another.

4. Scatterometers:
   a. These devices have directional ambiguities.
   b. Clouds, water vapor and precipitation affect the signal in non-linear ways.
   c. Quality control is an issue.

5. Dropsondes have very different characteristics than do RAOBS, and there are fewer of them to determine performance statistics.

Derber went on to list characteristics of data useful to operational NWP:

1. They have to be available when needed. The full suite of data assimilation, models and model output, runs on a very tight schedule. If the observations miss the global analysis cycle, they can still be entered into the background field at the next analysis cycle. For some data, however, much of the value could be lost in that delay. Regional forecast systems have very tight windows, sometimes an hour or less. Data missing a cycle normally would not be useful for the following cycle.

2. The data have to be in a standard format. BUFR, for example, is the World Meteorological Organization (WMO) standard. Data that are not in a standard format require larger amounts of resources to assimilate, and normally are not.

3. The data and the data stream have to be stable. This means that the instrument performance, calibration and processing algorithms are stable. Again, the effort to make changes is very large and can only be justified infrequently. The data flow needs to be supported, in most cases, on a 7 day per week, 24 hour per day basis. That means when system problems are encountered, the capability needs to be there to make corrections. Erratically performing systems produce data that can cause serious problems in the data assimilation.

4. Need to be able to detect those situations were the forward model is not adequate or there are gross errors in the observations. The forward model may fail over land or ice, as an example. There need to be sufficient observations to be able to cross-check the significant departures from the first guess. The departure may be valid, but without confirmation it most likely will be ignored.

5. Scales represented by the observations (determined by the background error covariances in this instance, and not by the grid size) can be too small to be resolvable by the data assimilation system.

6. There must be an accurate, fast forward model and an adjoint available for the data. These can range from the simple to the complex. There must be enough information about the

characteristics of the data to make accurate simulations of the observations. The forward model must be fast enough to be used operationally given the time constraints.

7. The data must provide a small error relative to the signal. The errors must be uncorrelated and the data must be representative of the physical and dynamical processes. The errors must be less than the overall model error.

8. The data must provide information that is above what is already available in the system, including the background field.

Significant progress has been made over the past 18 months in the development of the operational WRF 3DVAR data assimilation system. . The research state-of-the-art version of the WRF 3 DVAR is scheduled for 2006. The advanced four dimensional data assimilation (A4DDA) assimilation is likely to be implemented by 2010.

The most important components yet to be added to the WRF 3DVAR assimilation are:

1. Spatially varying background error covariances,

2. Airborne Doppler radial velocities,

3. Satellite/aircraft radiance data (both sounder and imager),

4. Assimilation of cloud and precipitation data, and

5. An appropriate moist balance scheme.

The ocean-coupled model data assimilation will focus on:

1. Upper ocean/mixed layer as being of primary importance,

2. Skin temperature, which is a primary measurement from satellites,

3. Bulk water temperature obtained from ship observations. The satellite retrievals are calibrated to the bulk temperature, and

4. Profiles of the thermocline and mixed layer depth which are provided by ARGO profiler floats and expendable bathythermographs.

In summary, the improved specification of the background error co-variance has top priority. Not all of the observations are useful. Useful observations meet the specifications given above. Significant progress over the last few years has been made in how to assimilate data from a wide range of sources. Current observations, however, are still not being used to the maximum possible, and some new observations have not yet been incorporated into the data assimilation schemes. The task of achieving an effective data assimilation scheme for a new observational data set may be on the order of 1-2 years from the time the data are reliably available. Data assimilation schemes can and should be as transportable to different platforms as the models themselves.

The following points were made during the question and answer period:

1. Cloud liquid water, cloud ice and direct measurements of wind, e.g., from airborne Doppler radars are the most important new observations to obtain.

2. The idea of a super observation (e.g., one observation made up of several), or gridded fields are not valuable for the data assimilation systems. Both cause problems, in part because the errors are not independent.

3. There is a need to have information on the boundary between liquid and frozen precipitation.

B.4 Land-Surface Hydrology (Robert Tuleya, GFDL)

Surface wetness is a major influence on the storm evolution at landfall. The GFDL model does try to include this effect, but the physics are not well developed. The gross features of the landfall can be modeled adequately, but significant details are lost.

One of the issues is that verification of the decay in the wind at landfall and the details of the precipitation is not adequate. The skill at predicting rainfall is just now being evaluated. The skill at predicting changes in intensity is roughly the same as predicting the landfall. Rainfall patterns, wind structure after landfall, and the interaction with convective events such as down bursts and tornadoes are not well predicted. One of the tactics is to look more carefully at case studies such as Allison to determine what happens to a hurricane at landfall.

B.5 Hurricane Microphysics (Scott Braun, NASA/GSFC)

Braun emphasized the complexity of the structures in hurricanes, including the mix of liquid, freezing and frozen water. These phases must be parameterized, but how? There are many schemes to consider. There are single mode schemes; for example, (1) warm rain at all heights, (2) simple ice phases with no mixed phase, and (3) rain below the freezing level and frozen precipitation above. Such models run quickly, but realism and value are lost. For hurricane microphysics, coarse resolution is greater than 3 km, and fine resolution on the order of 1.6 km. A mixed scenario is the most complex and takes the longest to run. There is a question, however, of the effective benefit to running the complex scenario operationally. It may not provide any useful forecast improvement.

A simple ice with no mixed phase is the best to use for models that have to be run quickly. This scenario, however, is not realistic of freezing and melting zones. The current mixed phase scenarios are inadequate for cloud ice processes. Too little ice is forecast at lower levels. It also gives too much graupel in simulations of many kinds of convective systems. Correcting any of these deficiencies should not be done by adjusting the drop size distributions. One needs to look at the distribution and amount of supercooled water and ice.

For grid sizes of 3-4 km, there are several issues in resolving features. The outer bands are not well formed at the scale of 3-4 km. One has to go to a grid size of about 1.5 km. The stratiform precipitation is not well developed at the larger scales and this has a serious impact on the forecasts of quantitative precipitation. There are some results that the 3-4 km grid size has a limited impact on intensity forecasts, but this needs additional research.

B.6 High Resolution Hurricane Simulations with MM5 and WAVEWATCH III (Shuyi Chen, Univ. Miami)

Using a vortex-following nested grid model with 1.67 km resolution in the finest mesh, the simulations of hurricane Floyd show that the simulated storm intensity is sensitive to the model grid resolution. In particular, it is sensitive to various parameterizations of surface fluxes and wind-wave coupling. The sensitivity increases as the model horizontal grid resolution increases in order to resolve the circulation of the hurricane eye and eyewall. These results indicate that the new and improved parameterizations for high-resolution coupled atmosphere-wave-ocean models are needed for improving hurricane intensity forecasts.

B.7 The Semi-Lagrangian Dynamic Core: A candidate framework for the Hurricane WRF (Gopal Sundararaman, NCEP)

A non_hydrostatic, semi_Lagrangian, dynamical core is being developed as a contribution to the multi_institutional Weather Research and Forecasting (WRF) initiative. This version is intended to complement the Eulerian dynamical core developed at NCAR.

Apart from the liberation of conventional CFL restriction and consequent gain of a longer time step in non_hydrostatic models operating at 1_10 km horizontal resolution, the application of higher order compact differencing techniques to the semi_Lagrangian model along the trajectories allows recovery of data at the new grid points without loss of information. Subsequently, better reproduction of vertical motions for hurricane intensity forecasting are expected.

Development of 3-D, dry explicit core with horizontal semi_Lagrangian advection of scalar is complete. Tests of the semi_Lagrangian approach and Eulerian approach (our model has either options) show nearly identical results for horizontal advection. The real gains are expected with the fully Lagrangian semi_implicit version that is currently under development. Performance of semi_implicit, semi_Lagrangian scheme for 3_D advection in the eye_wall region will be subsequently assessed after coupling with the existing WRF physics.

C. USWRP and NWS Goals

C.1 USWRP and the Hurricane Program (John Gaynor and Russell Elsberry)

John Gaynor (Director of the USWRP Interagency Program Office) gave a summary of the planning in the USWRP for the hurricane program. One of the four primary foci for the USWRP is landfalling hurricanes. Russ Elsberry noted that the USWRP needed to look at the issues and relate them to the work in progress to determine the gaps in the research program. Priorities needed to be identified, and opportunities for research announced to the community. From workshops such as this one, the USWRP needed to know how various programs such as CBLAST fit into the research. One of the critical issues was to be able to coordinate the research with model development within the funds available.

The USWRP picked nine projects in 2001 that fit with the need to transition research capability into operations. Those projects have associated metrics to determine the progress being made. Part of the pathway to operations is the Joint Hurricane Testbed (JHT). The research community needs to understand what that pathway is and what are the rules for using it. Without that understanding, researcher could very well be working on concepts that are either not suited for operational use, or that would take an inordinate amount of effort to implement operationally.

Naomi Surgi is leading the effort to develop the Action Plan for landfalling hurricanes that will detail the issues and give a time line for the research program. This workshop is one step in preparing the action plan. The landfalling hurricane action plan focuses on the first 5 years to about 2008. It will give time lines, milestones and mid-term goals. The action plan has several functions one of which is to give managers a tool to track the progress being made. Tracking is done by how well the science objectives are being achieved, the success with operational implementation from research, and the funding. Having the action plan and metrics gives managers a vehicle for future plans and funding requests.

For FY 2003, the USWRP needs to have priorities for research along with milestones and metrics for measuring progress. Some 50% of the NOAA funds for the USWRP are provided directly to academia and the private sector through competitive Announcements of Opportunity (AO). The AO for the JHT, for example, was written by the USWRP Science Steering Committee (SSC), and directed to the entire hurricane research community. The expectation is that the Hurricane AO for FY 2003 will be a joint effort between NOAA and the National Science Foundation (NSF). Coordination between NOAA and NSF needs to be strengthened so that all the hurricane research efforts are coordinated and focused on the priority issues.

During the discussion, several questions were asked about model development and potential transition from research to operations. Potential use of a testbed facility is being explored for WRF transition issues. Also many of systems and techniques used for CBLAST may have operational application as will other issues in the HWRF model development. How will that transition occur?. One question that needs to be addressed is how to obtain the information about the performance of the systems and their potential for operational use. One way to do that would be through examining the results of data assimilation and observing systems experiments to learn the impact of the observations on the NWP products. John Gaynor replied that use of new observations was a central part of the USWRP and that serious consideration would be given in the AOs to those kinds of issues.

C.2 The future of NWS hurricane modeling: The development of the operational HWRF prediction system

The Weather and Research forecast system (WRF) is currently under development by the U.S. research and operational modeling communities and will replace current mesoscale modeling capabilities for various mesoscale forecast applications at operational NWP centers including NCEP and AFWA beginning in 2004. The WRF for hurricane forecasts (HWRF) will replace the GFDL hurricane prediction system at NWS/NCEP in 2006. The HWRF will serve as the nations next generation operational hurricane prediction system, as well as serve as the primary research hurricane model to replace the MM5. Although much progress has been made at operational NWP centers in improving track forecasts over the past two decades, a focused effort at NCEP/EMC is now being directed towards improving intensity and hurricane related rainfall forecasts.

To meet the above forecast challenge, EMC’s hurricane modeling effort will address the relevant scientific issues on both the large scale tropical/extra tropical hurricane environment as well as on the hurricane scale. Advancing the NCEP NWP hurricane system on both scales is necessary to properly simulate the complex scale interactions between the physical and dynamical processes that describe hurricane motion, hurricane structure and intensity changes over the open ocean and at hurricane landfall. To this end, advances to the NCEP Global Forecast System (GFS) will also proceed with continuous model development and advanced data assimilation techniques. By 2010, the GFS will be a coupled atmosphere-ocean system with a strong ensemble component.

The HWRF will be operationally implemented as a coupled air-sea-land prediction system and by 2010, will run at high resolution (5-7km/64L). Model system development will include 1) **advanced observations** from a variety of atmospheric and oceanic platforms from both in-situ and satellite based platforms over various scales of motion; 2) **advanced data assimilation techniques** for both the environment and hurricane core circulation and 3) **advanced coupled model** with high resolution physics.

The following components of the NWP forecast system will be transferred to operations between 2006-2010:

1. **Advanced Observations:**

b) Environment - (e.g. winds, temperature moisture) from in-situ obs, e.g. G-IV, P-3's and advanced satellite observations on the next generation geostationary and polar orbiters. To describe the structure of the larger scale atmosphere/oceanic environment. Targeting strategies must be implemented operationally to take maximum advantage of sparse and expensive in-situ platforms.

c) Hurricane core circulation - observations from the NOAA G-IV to describe the hurricane core circulation from high altitude to the surface which may be supplemented with P-3 observations where available. Microwave data may also be useful in rainy areas. The airborne doppler radar data may be supplemented with 88-D radar data for storms approaching coastal areas.

d) Ocean - SST's, wave height, mixed layer information from satellites, in-situ platforms, e.g. altimeter, AXBT's.

2. **Advanced Data Assimilation:**

a) Environment - Advanced 4-dimensional data assimilation (A4DDA) capability for both atmosphere and ocean. This effort is proceeding in parallel to the A4DDA effort in the NCEP Global Forecast System (GFS).

b) Hurricane core - This effort is being developed at EMC to address the next generation vortex initialization. To this end, a local mesoscale data assimilation capability is being developed at EMC and will require substantial research and development to run as a cycled system and to meet operational data assimilation challenges.

3. **Required Model Development for the HWRF**

a) Coupling – Interactive atmosphere/ocean circulation with nested surface wave model and surface including hydrologic processes including stream flow and flooding.

b) Advanced physics for high resolution models:

- microphysics (liquid/ice)
- representation of convection
- air-sea interface (e.g. ocean/atmosphere boundary layer, surface waves)
- land surface coupling (vegetation, topography/friction) and hydrology (stream flow, flooding)
- radiation (interaction with microphysics, aerosols)
- turbulence, sub-grid scale mixing

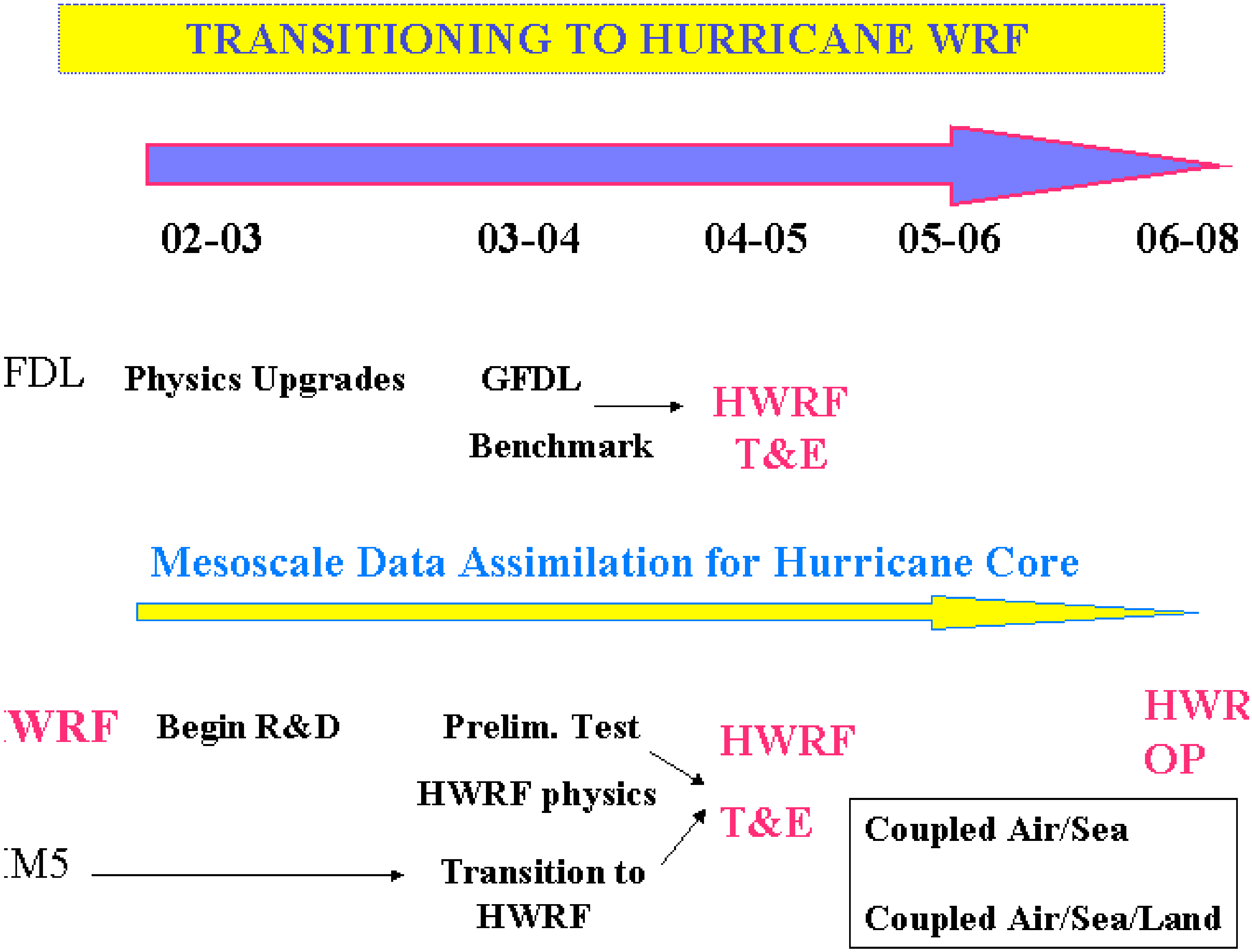
These physics will require substantial testing and evaluation (T&E) to determine the optimal model configuration for the initial HWRF operational implementation at NCEP in 2006. The initial HWRF implementation will run at 15km/42L with yearly incremental increases in both horizontal and vertical resolution to 5-7km/64L by 2010. In particular, sensitivity studies to physics including microphysics, representation of convection, atmosphere and ocean boundary layer parameterizations and land surface processes will need to be carried out over this period at several resolutions (horizontal and vertical) requiring substantial T&E for the full coupled HWRF prediction system.

4. Additional Hurricane Model Issues

a) Development of probabilistic guidance, e.g. ensembles
b) Adaptive observations and advanced targeting strategies
c) Verification suitable for the mesoscale

5. NCEP/EMC HWRF Implementation Plans

Over the next year the GFDL model will be upgraded with GFS model physics. It is anticipated that these upgrades will provide further improved GFDL track forecasts, thus the GFDL will provide the benchmark for the HWRF. A schedule of the transition of the GFDL model to the WRF framework is shown in fig. 1 along with the HWRF development, pre-implementation testing and evaluation of a coupled HWRF system in preparation to transition to operational implementation. Users of the MM5 are encouraged to align with these development and transitional activities. Further details on the operational pre-implementation plan including the necessary T&E of all HWRF components will be provided by NCEP/EMC.


TRANSITIONING TO HURRICANE WRF
02-03
03-04
04-05
05-06
06-08
FDL
Physics Upgrades
GFDL
Benchmark
HWRF
T&E
Mesoscale Data Assimilation for Hurricane Core
WRF
Begin R&D
Prelim. Test
HWRF physics
HWRF
T&E
HWR
OP
Coupled Air/Sea
Coupled Air/Sea/Land
M5
Transition to
HWRF

Appendix A: Agenda for Hurricane WRF Workshop 29 – 30 May 2002

Wednesday, May 29th

9:00 – 9:30	Stephen Lord and Naomi Surgi: Welcome, introduction and purpose of workshop
9:30 – 9:45	Russ Elsberry – Summary of San Diego workshop on tropical cyclone modeling

A. Forecaster assessment: Present and future forecast challenges

9:45 – 10:15	Richard Pasch – Summary of San Diego workshop on tropical cyclone modeling
10:15 – 10:30	David Reynolds – Hurricane QPF and inland flooding
10:30 – 11:00	BREAK

B. Scientific challenges for the Hurricane WRF

11:00 – 11:30	Dimitry Chalikov – Air/sea interactions
11:30 – 12:00	Henrik Tolman – Surface waves [WAVEWATCH]
12:00 – 1:30	LUNCH
1:30 – 2:30	John Derber – Data assimilation
2:30 – 3:00	Question and answer session
3:00 – 3:15	Robert Tuleya – Land surface hydrology
3:15 – 3:30	Scott Braun – Hurricane microphysics
3:30 – 4:00	BREAK
4:00 – 4:30	Shuyi Chen – High resolution hurricane simulations with MM5
4:30 – 5:00	Gopal – The Semi-Lagrangian dynamic core: A candidate framework for the Hurricane WRF

Thursday, May 30th

C. USWRP and NWS Goals

9:00 – 9:30 John Gaynor and Russ Elsberry – USWRP and the Hurricane program
9:30 – 10:00 Naomi Surgi – The future of NWS hurricane modeling: The development of the operational HWRF prediction system10:00 – 10:15 Jenni Evans – Charge for the working groups
10:15 – 10:45 BREAK

D. Working Groups

10:45 – 12:15 WORKING GROUPS
12:15 – 1:30 LUNCH
1:30 – 3:30 WORKING GROUPS
3:30 – 4:00 BREAK
4:00 – 5:00 GENERAL DISCUSSION: Summary of key workshop findings

WORKING GROUP THEMES

I Observations, Gulfstream IV upgrades and data assimilation

II WRF hurricane modeling: modeling physical processes for a high resolution coupled air/sea/land hurricane prediction system

Appendix B: Working Groups

I Observations, Gulfstream IV upgrades and data assimilation

Peter Black	NOAA/HRD
John Derber	NWS/EMC
Jim DuGranrut	NOAA/AOC
John Gaynor	NOAA/USWRP/IPO
Alan Goldstein	NOAA/AOC
Frank Marks	NOAA/HRD (co-chair)
Bob Maxson	NOAA/AOC
Jack Parrish	NOAA/AOC
Jim Roles	NOAA/AOC
Ward Seguin	NOAA/USWRP/IPO
Nick Shay	University of Miami/ RSMAS
Naomi Surgi	NWS/EMC (chair)

II WRF hurricane modeling: modeling physical processes for a high resolution coupled air/sea/land hurricane prediction system

Howard Berger	University of Wisconsin, Madison
Scott Braun	NASA/GSFC
Shuyi Chen	University of Miami/ RSMAS
Russell Elsberry	Naval Postgraduate School
Jenni Evans	The Pennsylvania State University (chair)
Brad Ferrier	NWS/EMC
William Frank	The Pennsylvania State University
Isaac Ginis	University of Rhode Island
Jim Giraytys	USWRP
Robert Hart	The Pennsylvania State University
David Nolan	Geophysical Fluid Dynamics Laboratory
Richard Pasch	TPC/NHC
Lynn Shea	University of Miami/ RSMAS
Robert Tuleya	Geophysical Fluid Dynamics Laboratory
Jerry Wegiel	AFWA
Da Lin Zhang	University of Maryland

Appendix C: Workshop Organizers

Naomi Surgi
EMC/NCEP
National Weather Service

Jenni L. Evans
Department of Meteorology
The Pennsylvania State University

Appendix D: Full Report of Working Group I – Data needs for the Hurricane WRF

This working group was tasked with defining the data types, sources, and strategies needed to initialize the HWRF model. Our focus was on a type of targeted observations, in the sense that the storm vortex was the target, needed to best initialize the vortex in the model using NCEP's advanced 3-D var. Below is an outline of those discussions. In all cases (data types, candidate instrumentation, flight strategies and recommended instrumentation upgrades) recommendations are given in **priority** order.

a) **Necessary types and resolution of observations to define the hurricane core circulation three-dimensional structure essential for model input:**

1) Wind

- radial resolution most important – 0.5-1.0 km
- height resolution next most important – high resolution (100 m) in ABL, outflow, and to resolve eyewall slope
- azimuthal resolution – at least wave #2

2) Moisture

- Vertical structure essential for validation.
- Critical in environment surrounding core. Model generated moisture will dominate the core.
- Height resolution critical – high resolution (100 m) in ABL.
- Azimuthal resolution next most important – at least wave#1
- Radial resolution – 10-20 km

3) Temperature profile

- Vertical structure essential for validation.
- Mean vertical profile, plus variation in radius and wave#1 in azimuth would be extremely useful for validation
- Height resolution critical – high resolution (100 m) in ABL and near tropopause.
- Radial resolution next most important – 10-20 km
- Azimuthal resolution – at least wave#1

4) Ocean temperature and heat content

- Essential for verification
- Radial and azimuthal resolution - critical between center and 200-250 km (24 h) ahead of storm
- Vertical resolution – mean values in the mixed layer critical – need to resolve mixed layer (10-20 m)

5) Microphysics/rain/reflectivity

- Essential for verification

- Vertical structure critical – resolution to resolve the melting level (250 m)
- Radial resolution next critical – resolve the eyewall (1 km)
- Azimuthal resolution least critical – wave #2

6) Ocean waves

- Essential for verification
- Azimuthal structure critical – resolve asymmetry in wave height and length – wave# 2
- Radial structure next critical – resolve radius of 8' and 12' seas - 20-50 km

7) Ocean currents: Essential for verification

8) Radiation: Essential for verification

b) Candidate instrumentation suites for observations to define the hurricane core circulation (NOTE: The instrumentation suite is current under review and may be amended)

1) Wind

- Airborne and ground based Doppler radars (limitation is winds only where it is raining, and poor vertical coverage near the surface because of ground clutter)
- Satellite Scatterometers/SAR and cloud drift winds (Weakness of scatterometer/SAR: only at the surface level. Weakness of cloud drift winds: coarse and uncertain vertical resolution.)
- Microwave radiometric retrieval (AMSU). Weakness: model assumptions for retrieval.
- Aircraft in-situ. Weakness: one level.
- Dropsondes. Weakness: limited spatial resolution
- Doppler LIDAR. Weakness: limitation to winds in non cloudy regions.
- SFMR. Weakness: only at surface.

2) Moisture

- Dropsondes/Rawinsondes. Weakness: limited spatial resolution
- Microwave radiometric/interferometry. Weakness: limited vertical resolution
- Aircraft in-situ. Weakness: one level
- DIAL LIDAR (NASA LASE)

3) Temperature

- Dropsondes/Rawinsondes. Weakness: limited spatial resolution
- Radiometric/interferometry. Weakness: limited vertical resolution
- Aircraft in-situ. Weakness: one level
- Microwave (NASA MTP)

4) Ocean Thermodynamics

- AXBT/Drifters. Weakness: limited spatial resolution
- Satellite IR. Weakness: no data in cloudy regions
- Satellite altimetery. Weakness: model interpretation
- Aircraft/satellite microwave

5) Rain/microphysics

- Buoys/ground stations. Weakness one level and limited spatial coverage
- Radar/polarization diversity. Weakness limited vertical resolution, limited view near coastline, and calibration between radars
- SFMR rain. Weakness one level surface
- Aircraft in-situ microphysics. Weakness one level
- Satellite. Weakness: limited to cloud/no cloud
- Profilers and sub-millimeter radars

6) Waves

- Radar altimetery (SRA)
- Laser altimetery. Weakness limited to no cloud or precipitation
- Fixed/drifting buoys. Weakness limited spatial resolution
- SAR imaging
-

7) Ocean currents

- AXCP. Weakness limited spatial resolution
- SAR interferometry
- CODAR – limited view near coastline
- Fixed/drifting buoys. Weakness limited spatial resolution

8) Radiation

- Satellite VIRS
- Aircraft in situ aerosol

c) Flight Strategies

1) To achieve radial resolution, need long radial legs to at least 450 km to resolve the radius of 35 kt winds.

2) To achieve the wave #2 azimuthal coverage, need at least 3 legs crossing the center 60 degrees apart

3) For data assimilation, need at least 12 hour repeat cycle.

4) Altitude should be as high as possible, although it is not clear that 12 km is optimum. It is clear that 6 km may be too low, particularly for moisture and temperature structure.

d) Instrumentation Upgrades needed for the Gulfstream

1) Communications to the ground to transfer the data to the model DAS – need a secure high-speed (at least 9600 bd) data communications link to the ground. Systems on the WP-3D currently are 100 bd ASDL, 2400 bd INMARSAT, and 9600 bd Globalstar. G-IV has 2/2400 bd INMARSAT systems and looking at 64000 bd upgrade. Need to interest NESDIS in this issue as they have the most experience.

2) Doppler wind capability: WP-3D has the ideal system, but doesn't fly high enough for the moisture and temperature requirements. G-IV has a nose radar that has Doppler capability, but not in the vertical. Looking at test of vertically pointing scanning Doppler radar (airborne profiler) for G-IV.

3) Moisture profiling: NASA (through CAMEX) has developed DIAL Laser (LASE) system for use on DC-8. Provides continuous vertical moisture and aerosol profiles above and below aircraft along flight track when not in heavy cloud. Not sure whether suitable for AOC aircraft.

4) Temperature profiles: NASA (through CAMEX) has developed microwave temperature profiler (MTP) system for use on DC-8 and ER-2. Provides continuous vertical temperature profiles 4-5 km above and below aircraft along flight track. Should be suitable for AOC aircraft.

5) Surface wind and rain: HRD and UMASS have developed SFMR to provide surface wind and rain estimates. Working with AOC on version that could be used on all AOC aircraft.

Appendix E: Full Report of Working Group II – Modeling physical processes for a high resolution coupled air/sea/land WRF hurricane prediction system

The charge to this working group on hurricane modeling was to (1) identify the critical physical processes that needed to be modeled for a high resolution coupled air/sea/land hurricane prediction system; (2) put into perspective the issues with these processes, such as what is known and unknown about them and the potential impact of the processes for the models; and (3) outline the research needed to be able to incorporate the processes in the models. This summary needs to give some priority to the efforts identified.

The working group divided its summary into three categories: (1) short-term research needed to transition in the 2005 time frame into the Hurricane WRF Version 1 [HWRF-V1]; (2) longer term (2005–2008 time frame) research that could contribute to a later version of the HWRF; and (3) opportunities to take advantage of current or planned field programs. The discussions of this group are recorded below, with a brief summary to be found in the summary section at the beginning of the report. In evaluating items for the final list, highest priority was generally given to the research in direct support of the transition to the HWRF. As with any priority system, however, work is needed across categories to ensure a consistent and long-term program, so some longer term research was included where appropriate.

There was substantial discussion of microphysics, radiation and parameterization of processes such as clouds and rain in the boundary layer. The need for resolution to at least 4 km was stressed. Some processes will have to be resolved at even smaller grid sizes.

The following comments indicate some of the more important areas where research is needed:

1) Parameterization at smaller scales, for example below 4 km, may not work for some processes. Studies are needed to determine what scales can be resolved. Further, it is likely that convection has to be implicit in the model and not parameterized as is generally the case.

2) Grid sizes of about 1 km should be able to resolve the largest eddies in the hurricane boundary layer. Even in models with a 1 km grid, those eddies are still parameterized, yet the fact that they are also beginning to be resolved leads to concern about “double counting” [artificially enhancing] the effects of turbulent processes in some flow regimes and over-smoothing turbulent flows by excessive mixing in others.

3) The important features of shallow layer convection will be difficult to resolve even if the grid size were to be 1 km.

4) The transition from the physics of the inner bands to those of the outer core are not known at scales even at 4 km. While the mesoscale processes in the eye wall are important to understand, how critical are they to improving the forecast of track and intensity in the coming five years? That question needs to be considered.

5) Basic research is needed on the processes in the turbulent eddies on the inner and outer edges of the eye wall. How does one paramaterize turbulence in general when the grid size is right on the boundary of the size of the turbulence?

6) Rainfall estimations over water are critical to understand the energy balances. Those estimates are poor at best.

7) The entire understanding of the phase changes of moisture needs serious study. Ice formation in updrafts, for example, is poorly understood. The role of graupel needs much better definition. Parameterizations of the phase changes range greatly in sophistication and none seem to give reliable results when compared to the observations that are available.

8) Changing grid sizes, as when using nested grids, can mask important physical processes, including turbulence. In fact there are serious issues of how to use different boundary layer physics in a model with several nested grids. How does one make the transition, for example, from a physical process being implicit in the model at one grid size, and parameterized in the same model at a different grid size?

9) The hurricane WRF should be useable across all of the grid sizes. But, that capability is well into the future. Because so many questions remain unanswered at the smaller scales, realization of that capability is well into the future.

10) Virtually all of the work has been done on and statistics exist for the storms in the strongest half of the intensity range. That not only biases the statistics, but ignores the very different importance of physical processes that occur in the weaker as opposed to the stronger storms. The weaker storms making landfall often cause the largest damage from flooding, for example.

WRF hurricane model validation was discussed at length. At NCEP there is a period of about 90 minutes from the analysis to the production of diagnostics. This means that the ability to do verification in real time is limited. At present the fields verified for the GFDL hurricane model are track and intensity. There are assumptions that if these two are correct, the other parts of the hurricane forecast are correct as well, and that clearly is not correct. The new verification packages include the central surface pressure, which is an indicator of the winds.

Wind structure over land for the 35 and 50 knot radii, and wind intensity will be part of the verification package. Changes of wind intensity with time over 6 or 12 hours will be included. Obtaining the ground truth for verification is a problem. This is true over the land and especially difficult over the ocean areas. Precipitation over land, for example, has not been well verified in the past even for the GFDL model. Verification over the ocean of the wind and precipitation fields is an important unresolved issue. These fields are intimately involved with the track and intensity of the hurricane. The ability to forecast these fields correctly is a direct reflection on the ability to forecast the track.

Building a set of test cases for model verification could require significant effort. Testing using historic cases may cause problems because there may not be enough data to be able to spin up the models to run on those cases. With the additional observing systems now being used and those expected in the future, future hurricane cases will be easier to use for model verification. One question that has to be answered is whether or not there should be a formal set of test cases. If so, there will be a substantial effort needed to generate the supporting material to be able to use that set for model testing.

The sub-group on ocean coupling (Isaac Ginis, Nick Shay, Shuyi Chen and Jerry Wegiel) set their goal as achieving the next generation coupled atmosphere-wave-ocean capability by 2005/6. the ocean model must be same resolution as the atmospheric (WRF) model (4-km). One approach would be to incorporate our work through High Performance Computing Modernization Office's Common High-performance Software Support Initiative (CHSSI) - Climate Weather Ocean (CWO-02): Infrastructure Development for Regional Coupled Modeling Environments project.